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*Original Article*

# Performance Investigation of Vector Control-based Induction Motor using Snetly Controller

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***Abstract*** *- Induction Motors are the most popular in power and industrial drives due to their simple operation, rugged construction, and free maintenance. In the last decade, the advanced technology of integrated power electronics-based drive enabled flexible operation and achieved effective speed control at each operating stage of the drive. Unlike scalar control, the performance of the induction motor is highly improved by using vector control methods. The vector control methods are categorized into direct field-oriented control (DFOC) and indirect field-oriented control (IFOC). Indirect Vector Control (IFOC) shows better dynamic performance and robust stability during zero and low-frequency speeds. Earlier, Digital Signal Processing (DSP), dSPACE, and microcontrollers are used for the hardware realization of the vector control methods. In the case of a hardware implementation of AC drives, FPGA (Field Programmable Gate Array) controllers provide better computation time and higher processing capabilities in comparison to conventional controllers. In this work, a novel real-time FPGA-based Snetly controller (Xilinx ARTIX-7 (XC7A200T) FPGA Controller with a 150 MHz clock frequency) is used to carry out a numerical simulation of an IFOC-based Induction Motor Drive. Firstly, the IFOC control algorithm is designed in MATLAB/Simulink software and then implemented in a Snetly real-time simulator. The Simulink results are validated and verified through the Snetly real-time controller. Further, the scope of this research article is useful for designing FOC-based Sensorless Induction Motor Drives effectively.*

***Keywords*** *- Field Oriented Control, Induction Motor, Snetly Controller, Vector Control.*

## 1. Introduction

Induction motors are widely used in industrial power applications due to their advantages like simple structure, low cost, high reliability, and easy maintenance.[1] The speed control of induction motors is majorly classified into two types: Scalar Control and Vector or Field Oriented Control. The scalar control method refers to the magnitude variation of control variables only, whereas the vector control method addresses controlling variables in both magnitude and phase alignment. Many applications with V/f Scalar open-loop and closed-loop methods are available in the literature. The technological evaluation in the field of power electronics and its allied areas enables research progress in the V/f method. In conventional practices, dSPACE, DSP and microcontrollers are used to realize the motor drives. [2,3] However, higher performance is required for medium-voltage and high-power drives. In such applications, the vector control method provides better dynamic performance than the former. [4–6]

The vector control is classified into DFOC and IFOC based on the generation of unit vectors. In DFOC, the required fluxes need to be computed for the unit vector generation with the help of machine terminal variables like voltage or current. In the case of IFOC, the unit vector generation is done by estimating rotor flux using the information obtained from the motor shaft, known as rotor speed. [7,8]

In vector control, the flux vectors in the induction motor design are selected in different ways, such as stator flux-oriented control, air gap or magnetization flux-oriented control, and rotor flux-oriented control.[9] This work presents the rotor flux-oriented (indirect field-oriented) control due to its advantages, such as ease of hardware implementation and better stability compared to other comparative methods.[30]

The major task for researchers and scientists is to develop fast and accurate real-time prototype controllers. These controllers are designed to reduce the computing time and complex calculations in the design. The importance of microcontrollers is greatly increased in the field of variable speed drive. For example, the STM32F4 family of microcontrollers is deployed for high-performance variable speed drives. However, the scaling time of applications has been increasing with conventional languages (C, C++) due to the complex calculations involved in the design. In addition, an expert is required for the computer systems to understand and develop the design architecture. For Industrial applications, the controller design should have high reliability, reduced hardware cost, and safety are the major parameters to make the control system stable and popular for real-time monitoring of the electrical systems. [3,11]

Recently, the main objective has been to develop real-time prototype controllers for the digital domain in the vector control of AC drives. In the digital domain, the control algorithm can be implemented either in continuous or discrete mode. The explicit Euler method is used to design the controller for higher sampling rates. However, this method of discretizing from the continuous state causes slower dynamics.[12–16] High-cost FPGA devices and systems with very-large-scale integration (VLSI) are required, but they produce higher power consumption with higher clock frequencies.[14] The controller needs to be discretized with the continuous system sampling dynamics to address the higher sampling period and better accuracy.[31] The vector control algorithm is used for many applications, including Sensor and Sensorless control of AC drives.

In medium-voltage and high-power applications, a Sensorless AC motor drive demands the rotor's exact position, angle, and speed.[18–21] The difference between the measured and actual values should be zero; otherwise, it creates an error.[27,28] In such cases, to deal with it with better accuracy and position, FPGA controllers are preferred to achieve a lower computation time with higher processing capability.[24] This work uses a novel FPGA-based Snetly real-time controller to study the IFOC-based induction motor drive. The proposed hardware investigation is different from traditional practices. The Snetly controller is equipped with the Xilinx ARTIX-7 (XC7A200T) FPGA Controller with a 150 MHz clock frequency. Unlike the conventional practices, the proposed Snetly controller enables the development and deployment have been in the same environment. Due to this advanced feature, additional licensed software with an expert and personal computer is not required. The simulation results are validated and verified by numerical simulation with the Snetly controller, which is presented in this work.

## 2. Materials and Methods

In this work, the IFOC-based induction motor is studied with the help of the Snetly real-time controller. The model is designed, and the corresponding algorithm is applied to the Induction motor drive. In this section, a detailed analysis of the method is presented for the development of the required hardware design.

### *2.1. Dynamic Modeling of Induction Motor*

The equivalent circuit of the induction motor is modeled in the synchronously rotating reference frame for the vector control method. The three-phase stator currents$(\boldsymbol{i_a}, \boldsymbol{i_b}, \boldsymbol{i_c})$ in the three-phase system are transferred into a two-phase stationary reference system $(\alpha - aixs, \beta - axis)$ and then converted into the rotating reference frame$(d - axis, q - axis)$ represented in the DC system. In vector control AC drive, the current components$(i_d, i_q)$ are adjusted to control magnetic flux and torque, respectively. The induction motor is modeled in the rotating reference frame as follows:[25]

The three-phase stator and rotor voltages can be written as,

$$v_s^{abc} = R_s i_s^{abc} + \frac{d\lambda_s^{abc}}{dt} \tag{1}$$

$$v_r^{abc} = R_r i_r^{abc} + \frac{d\lambda_r^{abc}}{dt} \tag{2}$$

The relationship between the flux and current components of the stator and rotor is given by

$$\begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix} \tag{3}$$

At arbitrary speed, the stator and rotor voltage can be written in the rotating reference frame as follows,

$$v_{ds} = -\omega_e \lambda_{qs} + p\lambda_{ds} + R_s i_{ds} \tag{4}$$

$$v_{qs} = \omega_e \lambda_{ds} + p\lambda_{qs} + R_s i_{qs} \tag{5}$$

$$v_{dr} = -(\omega_e - \omega_r)\lambda_{qr} + p\lambda_{dr} + R_r i_{dr} \tag{6}$$

$$v_{qr} = (\omega_e - \omega_r)\lambda_{dr} + p\lambda_{qr} + R_r i_{qr} \tag{7}$$

The Electromagnetic Torque $(T_{em})$ is given by

$$T_{em} = \frac{P}{2}\frac{L_m}{L_r}(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}) \tag{8}$$

### *2.2. Indirect Field Oriented Control*

The machine's torque and flux can be controlled independently using the vector control method like a separately excited DC machine. In this work, the modeled equations are described the indirect rotor field-oriented control of the induction machine drive.[25] The rotor flux vector is aligned with the rotor flux axis, representing the rotating magnetic field speed with exactly the calculated slip speed.

The rotor flux can be determined from the rotor voltage in the rotating reference frame providing an equal value of angular speed $(\omega)$ and synchronous speed $(\omega_e)$. The value of slip speed $(\omega_{sl})$ is defined as $\omega_{sl} = \omega_e - \omega_r$.

The rotor voltage is expressed in the squirrel cage induction motor using Equations 6 and 7;

$$v_r = \omega_{sl}\lambda_r + p\lambda_r + R_r i_r \tag{9}$$

$$0 = (\omega_{sl} + p)\lambda_r + r_r i_r \tag{10}$$

In the rotor circuit, the rotor current is given by

$$i_r = \frac{1}{L_r}(\lambda_r - L_m i_s) \tag{11}$$

Using Equations 9, 10, and 11, the rotor flux can be written as

$$p\lambda_r = \frac{1}{\tau_r}[L_m i_s - (1 + j\omega_{sl}\tau_r)\lambda_r] \tag{12}$$

Equation 12 can be written as,

$$\lambda_r\big(1 + \tau_r(p + j\omega_{sl})\big) = L_m i_s \tag{13}$$

In rotor flux-oriented control, the rotor flux is estimated by using the equations $\lambda_{qr} = 0$, and $\lambda_r = \lambda_{dr}$; the rotor current is given by $i_s = i_{ds} + ji_{qs}$; The block diagram of rotor flux-oriented control is shown in Figure 1.

The expression can be written as

$$\lambda_{dr} + \lambda_{dr}\tau_r p + \lambda_{dr}\tau_r j\omega_{sl} = L_m i_{ds} + L_m j i_{qs} \tag{14}$$

From Equation 14, the real and imaginary parts are given by

$$\lambda_{dr}(1 + \tau_r p) = L_m i_{ds} \tag{15}$$

$$\lambda_{dr}\tau_r\omega_{sl} = L_m i_{qs} \tag{16}$$

The slip speed and the rotor flux are written using Equation 15 and 16, with $\tau_r$is kept constant.

$$\omega_{sl} = \frac{L_m}{\tau_r}\frac{i_{qs}}{\lambda_{dr}} \tag{17}$$

$$\lambda_r = \lambda_{dr} = L_m i_{ds} \tag{18}$$

Hence, the currents $i_{ds}$ $i_{qs}$are represented to produce the induction motor's rotor flux and magnetic torque. They can be computed using the above equations as follows;

$$i_{ds} = \frac{1+\tau_r p}{L_m}\lambda_{dr} \text{ and } i_{qs} = \frac{T_{em}}{K_T\lambda_{dr}};\ \text{where } K_T = \frac{P}{2}\frac{L_m}{L_r} \tag{19}$$

### *2.3. Snetly Controller*

This paper uses an FPGA-based Snetly real-time prototype controller to study the IFOC method for the induction motor drive. The hardware setup consists of a three-phase bridge rectifier, a Semikron inverter, an incremental encoder, an Induction motor with load, and Snetly real-time controller with a Snetly output window. The proposed controller is built with Artix®-7 XC7A200T FPGA to enhance the processing capability and limit the computation time.[26]

In conventional practices, firstly, the model is designed in a software environment, but the Snetly platform is equipped to design and deploy in the same environment. The hardware schematic with the Snetly controller is developed, as shown in Figures 4 and 5. In this hardware, a three-phase AC supply is supplied to a bridge rectifier to convert AC into DC supply. Using DC Link, the converted DC supply is fed to the inverter. The Inverter output terminals are connected to the induction motor, and an incremental encoder is mounted on the motor shaft to measure the speed of the motor. The PWM signals and ADC interface are connected to the Snetly real-time controller, as shown in Figure 2.

### *2.4. System Design*

The control algorithm is designed in MATLAB/Simulink environment, shown in Figure 3. The overall block diagram contains three phase induction motor, a two-level inverter with an SVPWM algorithm, and FOC controller blocks. Table 1 shows the Induction Motor parameters used for the Simulink and the Snetly Controller.

## 3. Results and Discussion

The performance analysis of the IFOC-based induction motor drive is observed under the no-load condition with a reference speed of 900 rpm. The various parameters like Speed$(\omega_r)$, Electromagnetic Torque$(T_e)$, d-axis current $(i_{sd})$, and q-axis current $(i_{sq})$ waveforms are observed.

Under the no-load condition, the motor reached the reference speed of 900 rpm or 94.2 rad/sec. Figure 7 depicts the electromagnetic torque response was observed under no load conditions. The current controllers are set to be the desired points shown in Figures 8 and 9.

The FOC controller is run for different load conditions to verify the robustness and effectiveness. Figure 10 depicts speed response under various load conditions. The load torque is applied at different time intervals with a reference speed of 94.2 rad/sec, as shown in Figure 11. The load torque is applied for the different time intervals of 0 sec, 1.75 sec, 3 sec, and 4.75 seconds and both d-axis and q-axis currents are observed, as shown in Figures 12 and 13.

The Simulation results are verified and validated using the Snetly controller, as shown in Figures 14 and 15. Under load and no-load conditions, controller performance is observed for speed, torque, and current controllers. The controller provides the exact response as obtained in the simulation. The major objectives of using this controller in terms of fast computation, robust performance, and low computational burden in which complex calculations are getting involved in modern AC drives for reliable operation in power and industrial applications. The FOC-fed Induction Motor using Snetly Controller provided satisfactory results.

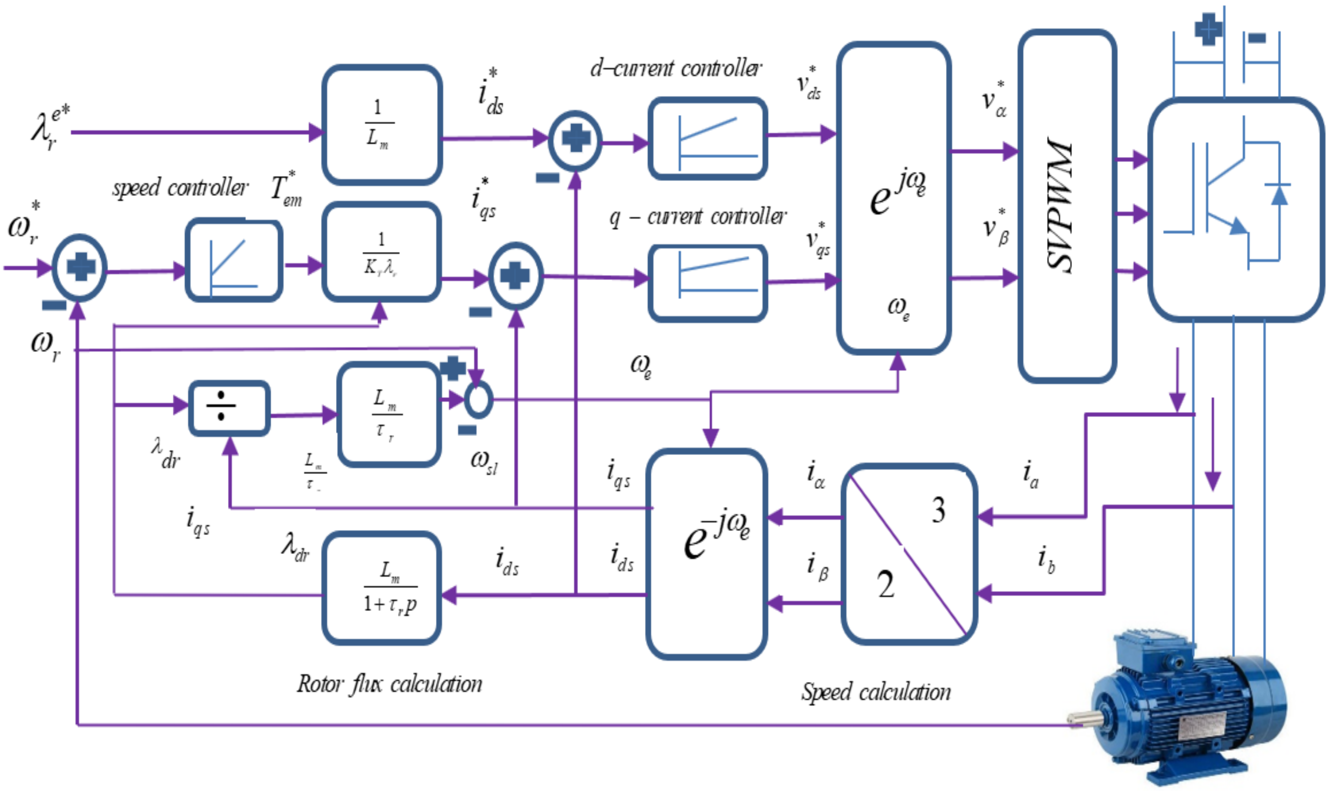


**Fig. 1 The architecture of the Indirect Field Oriented Control**

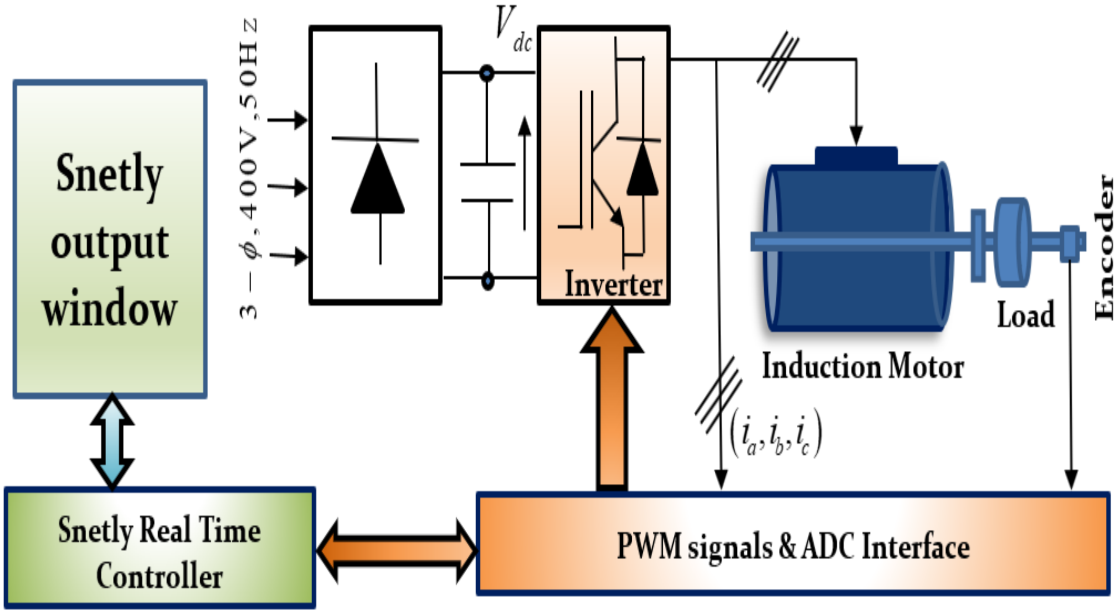


**Fig. 2 Schematic of FOC-based Induction Motor Drive**

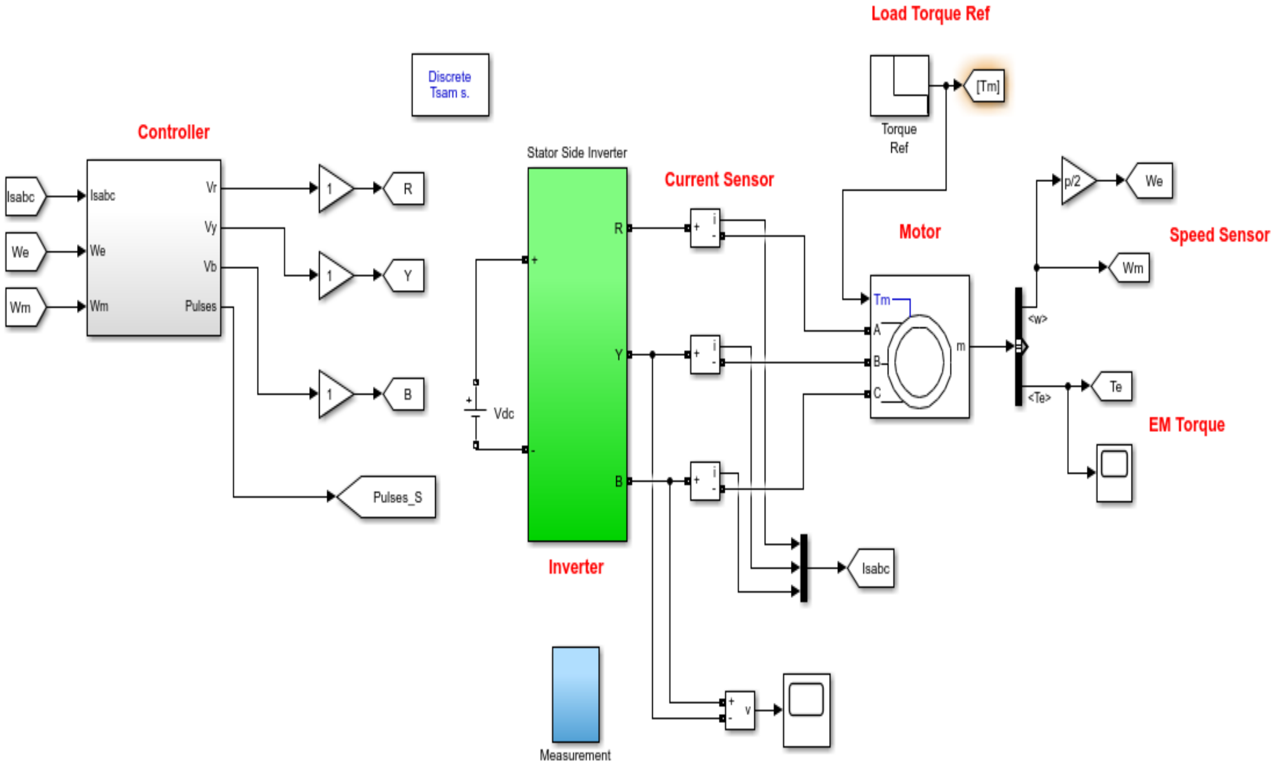


Fig. 3 Schematic of FOC-fed Induction motor drive in Simulink

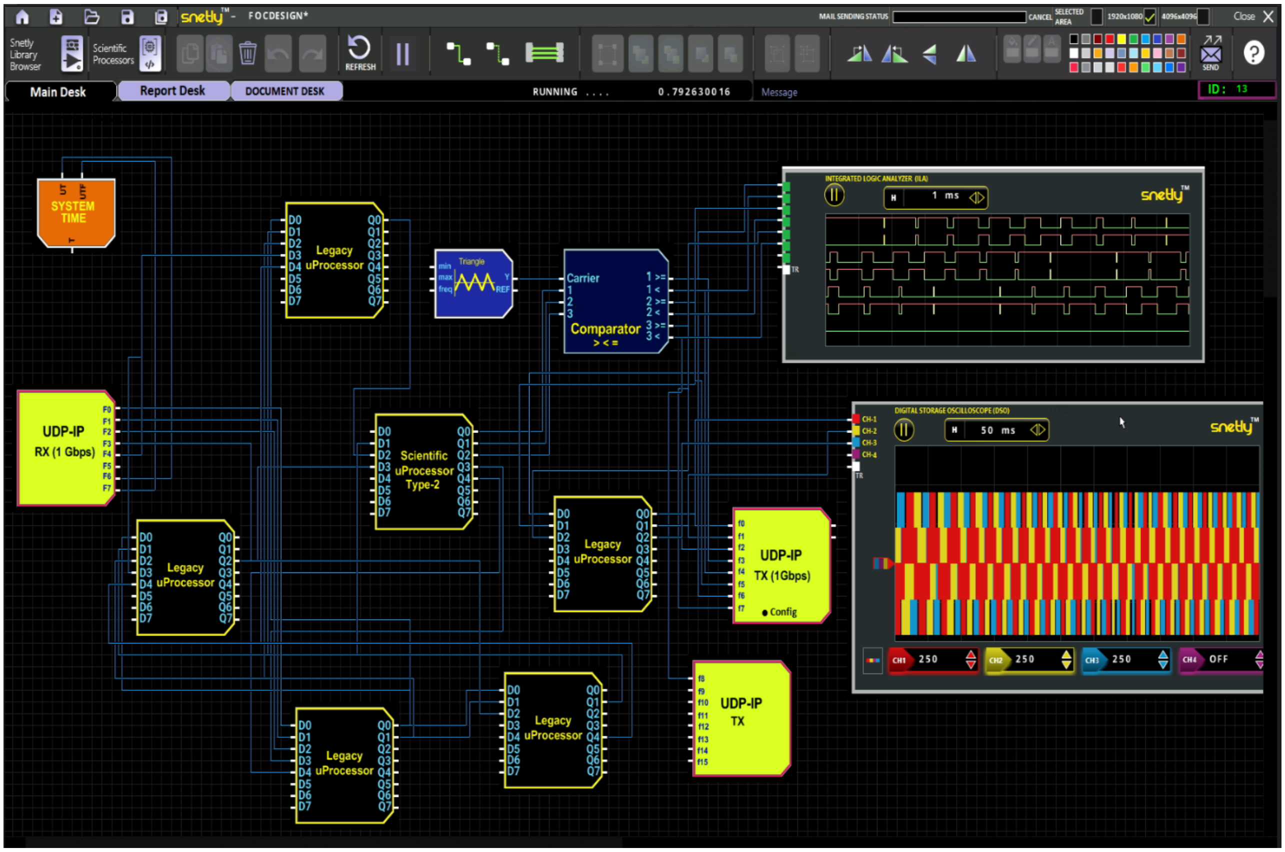


Fig. 4 The FOC fed IM drive design in Snetly Controller

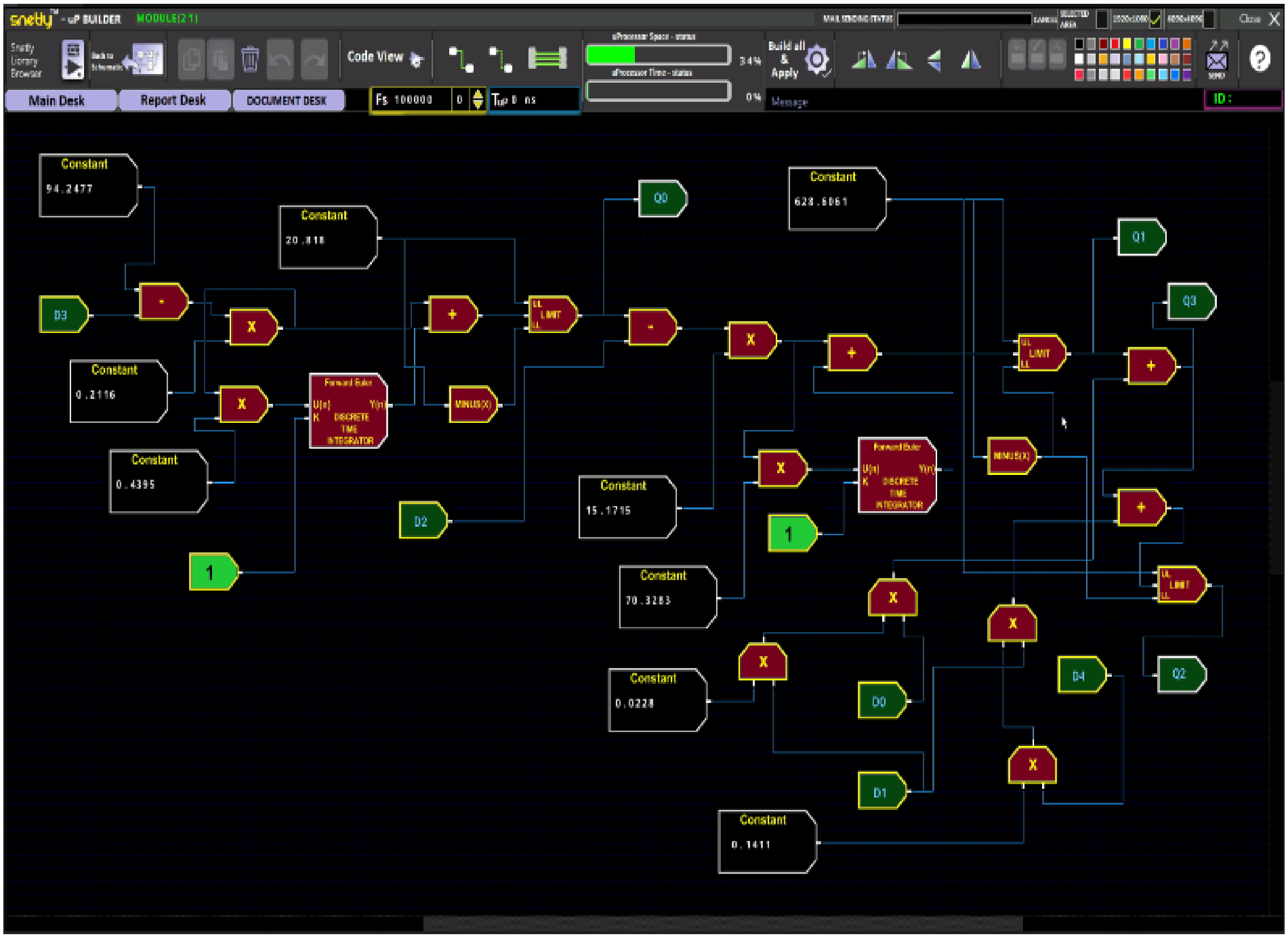


**Fig. 5 FOC design in Snetly Controller**

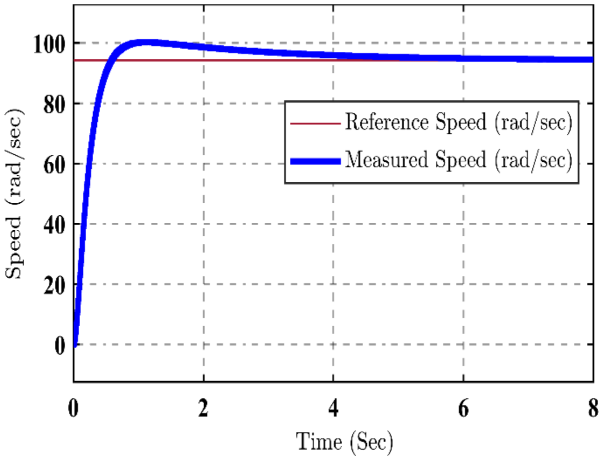


**Fig. 6 Speed response under no load condition**

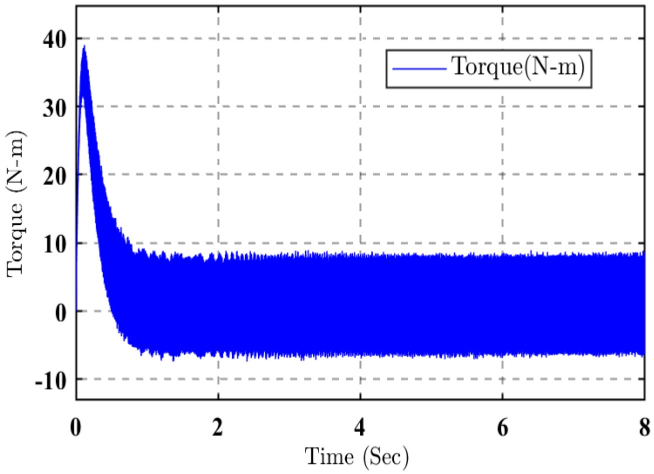


**Fig. 7 Torque response Speed response under no load condition**

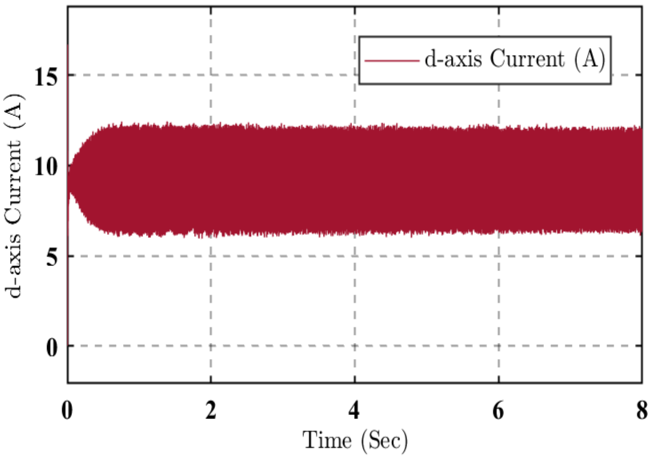


**Fig. 8 d-axis Current response under no load condition**

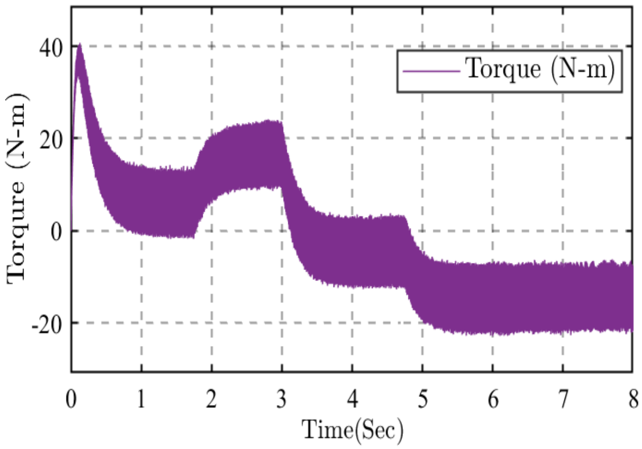


**Fig. 11 Torque response under the different loading conditions**

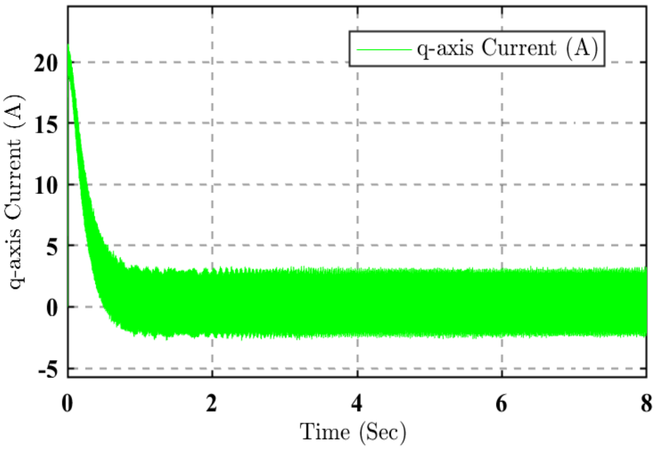


**Fig. 9 q-axis Current response under no load condition**

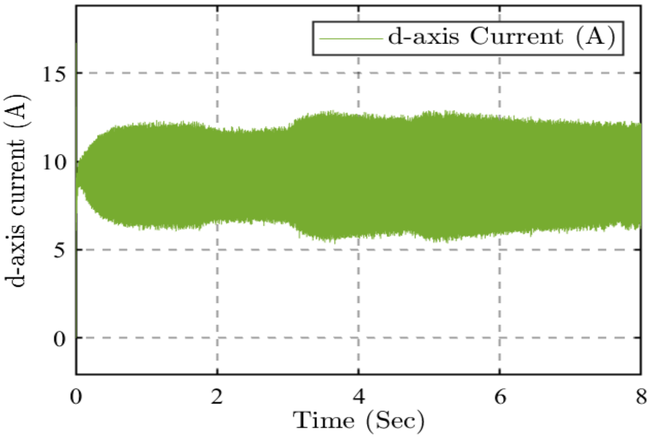


**Fig. 12 d-axis Current response under the different loading conditions**

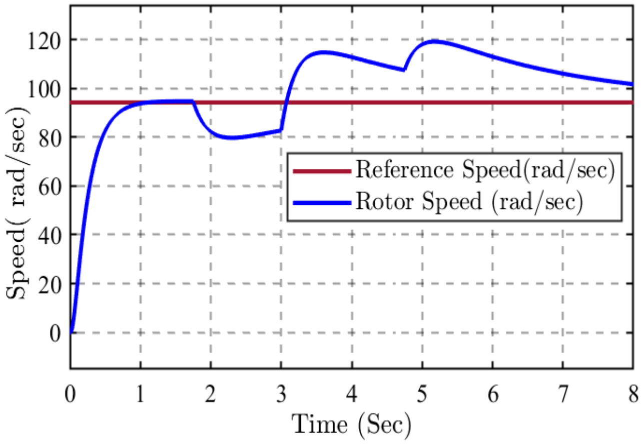


**Fig. 10 Speed response under the different loading conditions**

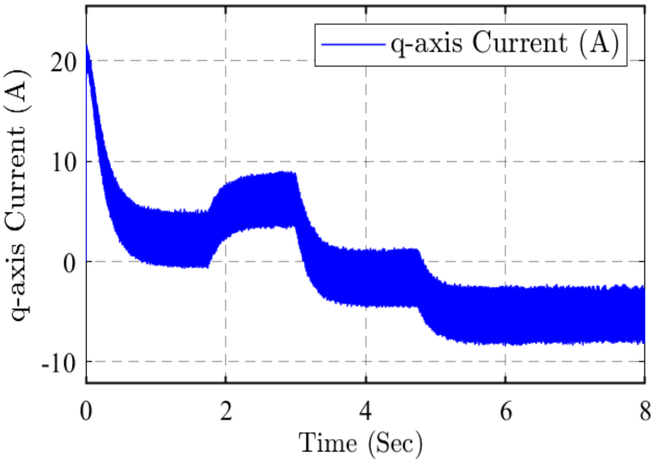
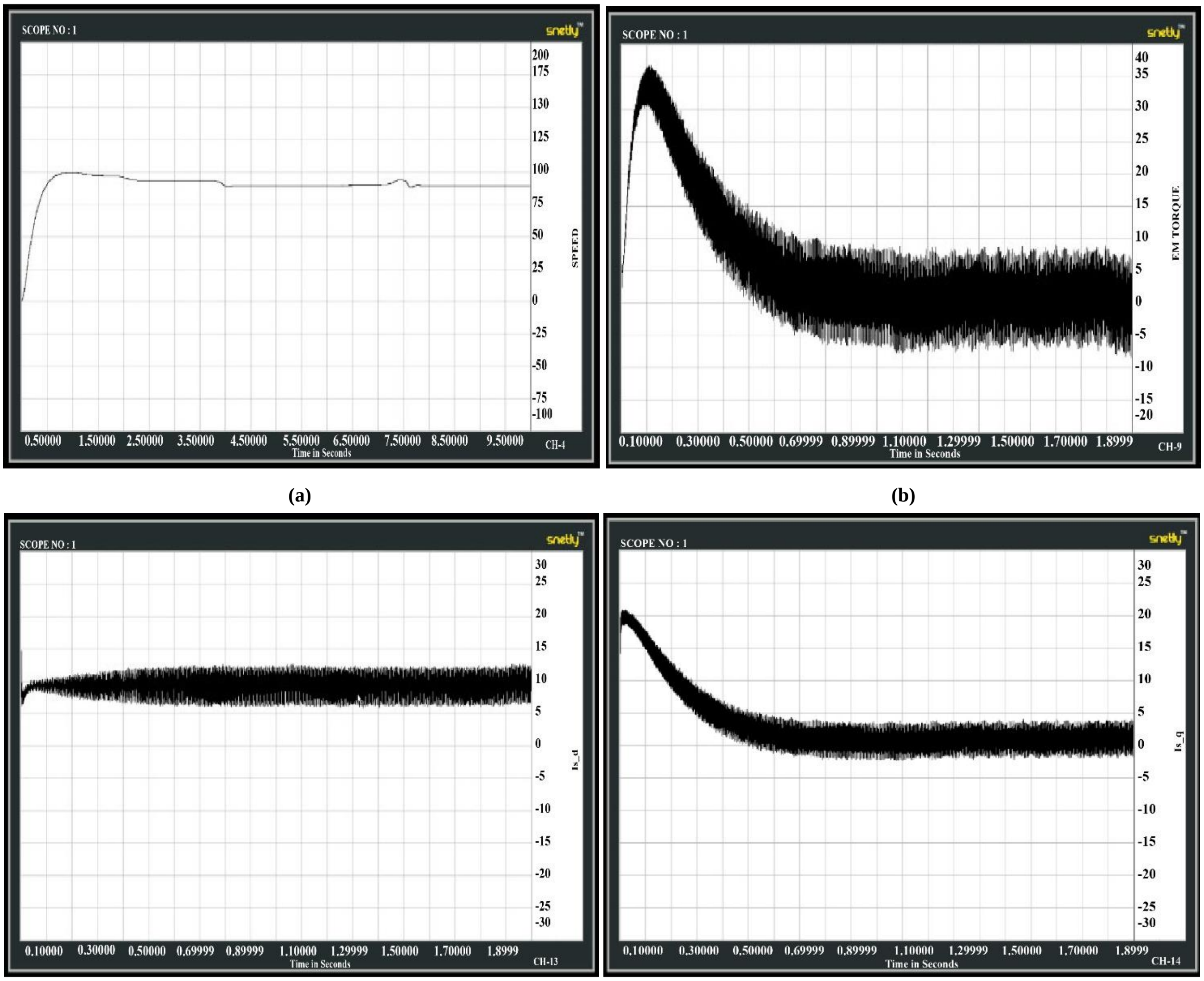


**Fig. 13 d-axis Current response under the different loading conditions**

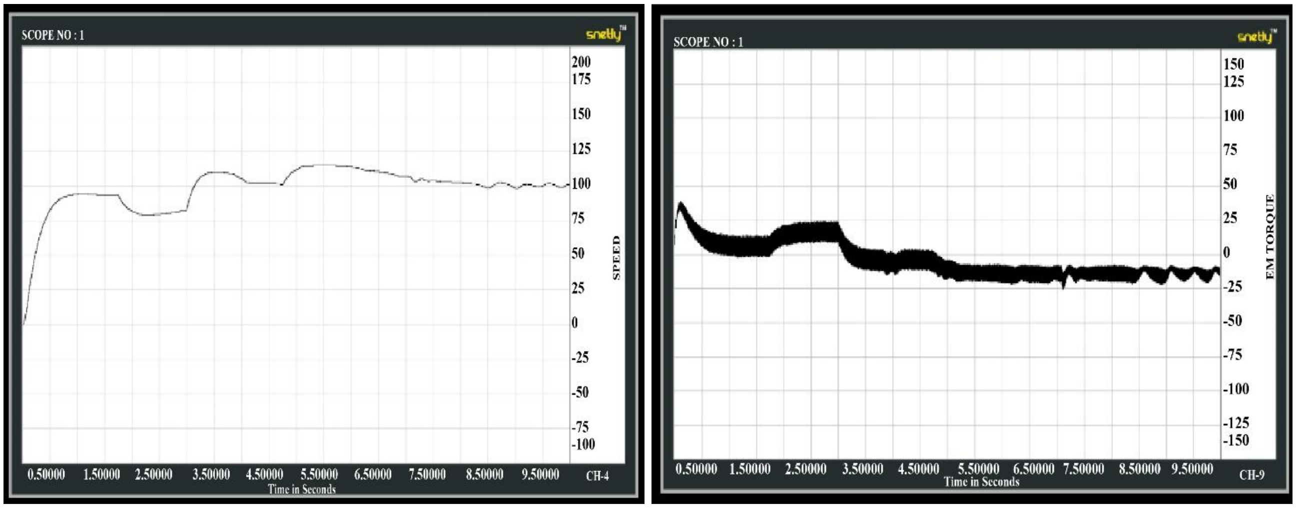


**(a)** **(b)**

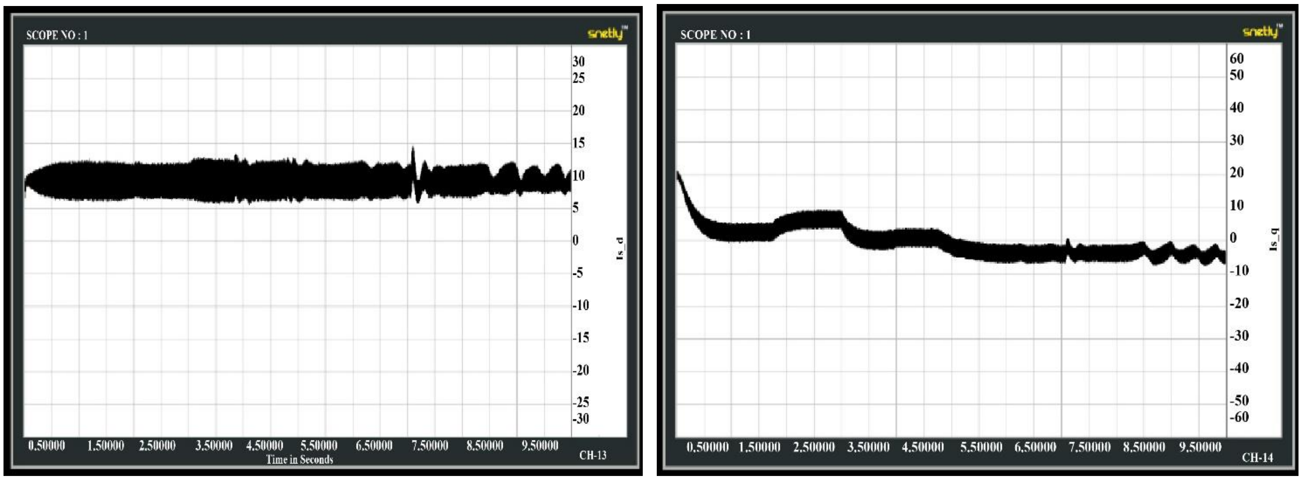
**(c)** **(d)**

**Fig. 14 The IFOC-fed IM drive results under no load condition**

**(a) Speed$(\omega_r)$ (b) Electromagnetic Torque$(T_e)$ (c) d-axis current $(i_{sd})$ (d) q-axis current $(i_{sq})$**



**(a)** **(b)**



**(c)** **(d)**

**Fig. 15 The IFOC-fed IM drive results for different load conditions**

**(a) Speed** $(\omega_r)$ **(b) Electromagnetic Torque** $(T_e)$ **(c) d-axis current** $(i_{sd})$ **(d) q-axis current** $(i_{sq})$

**Table 1. Parameters of the Three-Phase Induction Motor**

| Squirrel Cage type<br>Power, P = 4 [kW], Voltage, V = 415 [V], Frequency, F = 50 [Hz], No. of Poles = 6, Rated Speed, N =1000 [rpm] | |
|---|---|
| Stator Resistance | $R_s$= 2.86 [$\Omega$] |
| Rotor Resistance | $R_r$= 2.86 [$\Omega$] |
| Stator Inductance | $L_s$= 0.1639[H] |
| Rotor Inductance | $L_r$= 0.1639[H] |
| Magnetizing Inductance | $L_m$= 0.1521[H] |

## 4. Conclusion

In variable speed drive applications, vector control methods are much more interesting than scalar control methods. The former method enhances the dynamic performance of the drive generally used for high-performance system applications. The latter method is used in low-power applications due to its parameter sensitivity. However, The complexity of its equations and the non-linearity of the induction motor increase with vector control methods. In such cases, advanced real-time prototype digital controllers are required to realize the control algorithms in real-time hardware applications. In this work, a novel FPGA-based Snetly real-time controller is used for the IFOC method to address the problems in the conventional practices of hardware implementation. The controller can compete with advanced microcontrollers in terms of cost, complexity, and reliability. Unlike the traditional controllers, the model design could be done in the same environment, which is highly needed for monitoring the control system of the industrial drive. The primary work of this paper is FOC fed induction motor modeled and designed in the MATLAB/Simulink Software. To verify the robustness and effectiveness of the controller, an IFOC-based Induction motor is validated and verified using numerical simulation with the help of a Snetly real-time simulator. Further, to reduce the hardware complexity and cost, this can be a good choice in the field of Sensorless AC drives.

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